Structural Acoustics and Hydroacoustics Phenomena in Finite Fluid-Filled Pipes

PI: Minami Yoda†
Georgia Institute of Technology
Woodruff School of Mechanical Engineering
Atlanta, GA 30332–0405
Phone: (404) 894–6838
Fax: (404) 894–8496
E-mail: minami.yoda@me.gatech.edu
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ONR program officer: Luise Couchman

Long-term Research Objective:

The scientific objectives of this project are:

1. To describe and characterize the physical mechanisms which determine how most of the noise radiates from a finite fluid-filled pipe with turbulent flow.
2. To determine criteria which estimate the relative importance of these various mechanisms.
3. To develop experimental and analytical techniques for investigating turbulent flow-structure (hydroacoustic) interactions.

S&T Objective:

To provide design guidance in terms of minimizing detectable noise in future Navy vessels.

Approach:

The primary radiation mechanisms are identified using an axisymmetric model of a pipe-hull coupling. The analyses neglect torsion but incorporate fluid loading, elastic thin-walled shells, mass loading at the pipe-hull coupling, and variable material and geometric properties for both the pipe and hull elements. The problem will be analyzed in both the low- and high-frequency regimes. The goal of the analytical part of the study is to identify the important regimes for this problem, and to provide experimental design guidance.

The experimental part of this project will investigate turbulent flow-structure interactions and how they affect noise radiation from the pipe-hull coupling. This effort will take advantage of the new Georgia Tech Underwater Acoustics Facility, equipped with state-of-the-art near-field acoustic, laser-Doppler vibrometry and laser-Doppler anemometry instrumentation.

S&T Completed:

We recruited in July 1999 a "new" graduate student, Jayme Caspall, who will be completing his PhD based on this research. Mr. Caspall, formerly a Research Engineer at the Georgia Tech Research Institute, will be a major asset to this project with his extensive structural and underwater acoustics expertise in the CAVES and CACTISS programs.

In the high-frequency regime, the vibration wavelengths are significantly smaller than the diameter of the pipe *D* and hull curvature. The pipe is therefore be approximated as a fluid-filled

† Co-Author: Jayme J. Caspall (E-mail: jayme.caspall@gtri.gatech.edu)

thin-walled cylindrical shell with an axisymmetric massive termination of mass m, while the hull is modeled as an infinite fluid-loaded flat plate. As a first step, the problem of a fluid-filled rigid cylindrical duct with an infinite flange has been analyzed considering the axisymmetric and first two azimuthal modes. The "cut-on" frequencies, or the minimum frequency for waves to propagate, for a $D = 35.6$ cm pipe are presented in Table I. As expected, they increase rapidly with both m and n[1]; for the purposes of this research, we will only consider the three lowest cut-on frequency modes: $m = 0$ and $n \leq 2$ (highlighted in Tbl. I). Although the cut-on frequencies for all the non-axisymmetric modes are all well in excess of 1 kHz, or beyond the range of interest for most structural acoustics problems, a few of the higher-order modes will be included to investigate mode coupling (*e.g.* higher-frequency to lower-frequency).

	$n = 0$	1	2	3	4
$m = 0$	**0 Hz**	**2472**	**4100**	5640	7140
1	5144	7158	9004	10762	12464
2	9420	11462	13386	15234	17028

Table I: Minimum propagation frequencies for 35.6 cm diameter rigid pipe.

Noise radiation, in the form of typical beam radiation patterns obtained by numerically solving the Rayleigh integral at frequencies $f > 5$ kHz (well above the cut-on frequencies) and $D =$ 35.6 cm, is presented in Figure 1 for $m = 0$ and $n = 0$ and 1. The pipe exit is the space between the two dark triangles on the left. Here, the pressure is normalized by the on-axis value for the (0,0) mode at the same wavelength λ. For a uniformly partitioned velocity profile, the higher-order modes increase the angular coverage of the radiation pattern with side lobe maxima as large as 25% of the primary peak.

Impact/Navy Relevance:

In the next generation of submarines, detectable noise will be minimized by mounting internal machinery on an internal cradle attached to the hull using vibration-damped mounts. In these designs, the last remaining rigid hull connections are the seawater systems used to cool the reactors, condensers, and electronics. These continuously operating cooling systems will therefore become the primary flanking path for radiated machinery noise in future submarines.

Although efforts are currently underway to characterize vibration sources (*e.g.* valves and bends) inside the submarine, these vibrations are radiated as noise only where the pipe connects to the hull. This research is therefore motivated by the question, *"How do these vibrations radiate from the pipe-hull coupling?"*

Our present understanding of how noise radiates from submarine sea-connected piping systems is extremely limited. On current subs, the seawater exit at the hull through massive,

[1] n is the azimuthal mode number and m is the index of the set of solutions to the recursive relation

$$nJ_n\left(\frac{k_{r,mn}D}{2}\right) = \frac{k_{r,mn}D}{2} J_{n-1}\left(\frac{k_{r,mn}D}{2}\right).$$

hydraulically actuated primary and backup valves. Internal vibrations could radiate as noise from the pipe exit in two forms:

1) Noise due to hull vibrations, either due to:
   a) internal fluid-borne and structure (pipe, valve)-borne waves coupling to hull waves; or
   b) exit flow-induced vibrations; and
2) Noise carried by the exit flow, either due to:
   a) internal machinery; or
   b) the turbulent exit flow itself.

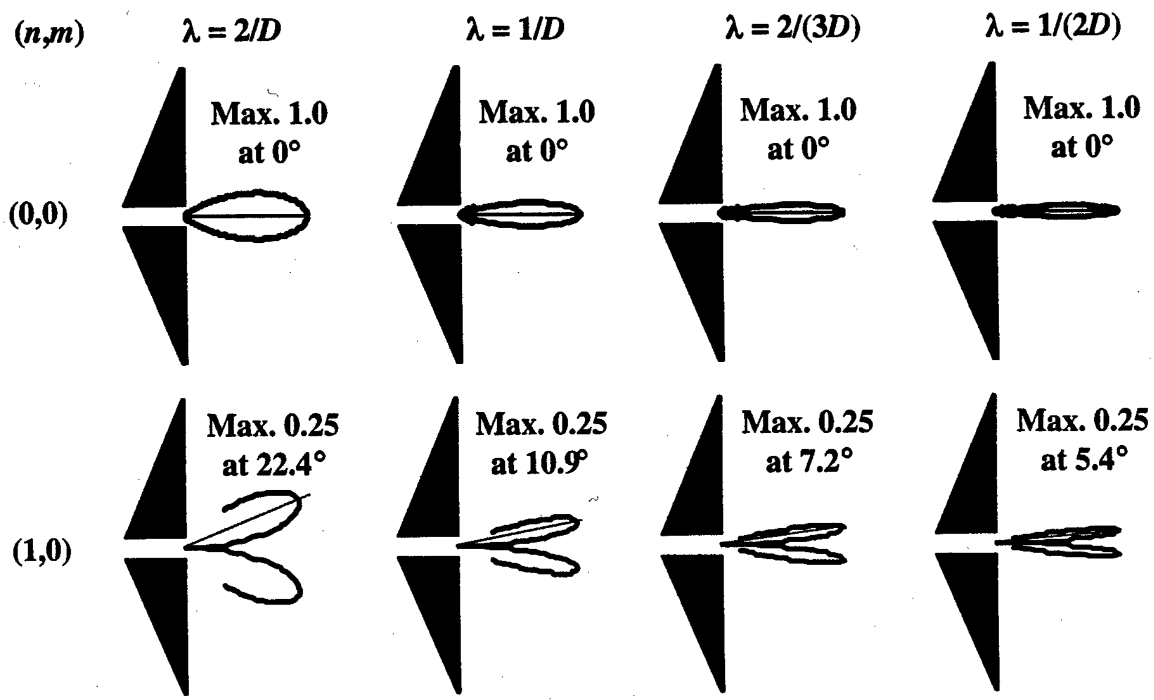

Figure 1: Beam radiation patterns for a rigid cylindrical duct at wavelengths of one, one-half, one-third and one-quarter pipe radii.

Planned Research Efforts:

A fundamental understanding of wave transmission and propagation in this geometry would be valuable in a wide range of situations where a pipe loaded with some given mass (representing, for example, valves, a flange or some type of seal or joint) transports fluid into a reservoir. This work will help determine if the seawater systems will be a major flanking path for radiated noise, and, if so, provide design guidance on developing "quiet" seawater systems which minimize noise radiation.

Planned S&T Efforts:

The next step in the high-frequency model analysis will be the analysis of a fluid-filled semi-infinite elastic cylindrical shell with massive axisymmetric termination. Basic questions to be answered in the shell analysis include:

1) How does the massive termination affect transmission of these modes past the mass?
2) How significant is mode coupling between fluid-borne and structure-borne waves?

The solutions from this shell analysis will be used to impose appropriate external ring loads on the "hull" modeled as an infinite fluid-loaded plate. Issues of interest for the high-frequency plate analysis include:

1) Is transmission through the massive termination sufficient to excite hull waves? If so, how efficiently do these internal structure-borne waves couple to hull vibrations?
2) What are the effects of hull thickness and material properties?

The pipe-hull coupling will then be analyzed in the low-frequency regime. In this regime, the vibration wavelengths will be large compared with the pipe diameter D and comparable to hull curvature. The pipe and massive termination will all be lumped into a single mass m with rotational inertia J imposing a normal (radial) point force and normal and axial moments on the hull, approximated by a fluid-loaded cylindrical shell. Using lumped-elements analysis, the impedance of the hull for a given curvature, thickness and material properties with respect to forces and moments will be determined and related to the properties required to excite hull resonance.

The analyses described here only address how internal structure- and fluid-borne vibrations radiate as noise. They will not give us any insight, however, into how the exit flow affects radiated noise. The latter half of this study will therefore involve scaled experiments of these models to both verify our previous analysis and to investigate turbulent flow-structure interactions.

Why would we expect any significant flow-structure interaction effects? The exit flow, a turbulent jet, will have a resonant vortex shedding frequency for typical submarine sea water systems of 1–10 Hz. Based on velocity fluctuation spectra, almost 25% of the turbulent shear stresses in the exit flow are contained in these vortices or eddies (Bradshaw *et al.* 1964). This implies that the forcing due to vortex shedding at the pipe exit is significant compared with the fluid momentum flux and at a frequency range which could efficiently radiate as noise, especially if coupled to hull waves.

The experiments will use the new Georgia Tech Underwater Acoustics Facility, a 40′ × 26′ × 24′ low-frequency facility scheduled for completion in August 2000. The axisymmetric pipe-hull geometry will be "floated" on the free-surface of the water, with a simple pump providing the turbulent flow (Fig. 2). Shakers will be used to excite the various pipe modes. Laser-Doppler vibrometry (LDV) through air will be used to measure both pipe and hull vibrations, and laser-Doppler anemometry (LDA) and flow visualization will be used to monitor the turbulent exit flow. The near-field hydrophone array will be used to directly measure the radiated noise due to both hull waves and exit flow. These studies will build upon the capabilities of this unique state-of-the-art facility and our in-house expertise in LDV and turbulent flow diagnostics.

References:

Bradshaw, P., Ferriss, D. H. and Johnson, R. F. (1964) Turbulence in the noise-producing region of a circular jet. *Journal of Fluid Mechanics* **19**, 591.

Other Sponsored Science & Technology:

Fluid dynamics aspects of liquid protection schemes for inertial fusion energy reactor first walls. Dept. of Energy. $242,580. 8/1/98–7/31/01.

Investigation of thermal-hydraulic phenomena in the APT tungsten target annuli. SE Consortium Accelerator Production of Tritium Project Ofc. $162,000. 9/1/98–8/31/99.

A velocity field measurement technique in the forming jet and on the forming table. Georgia Tech/Inst. for Paper Sci. & Tech. Seed Grant Program. $40,000. 8/1/98–6/30/99.

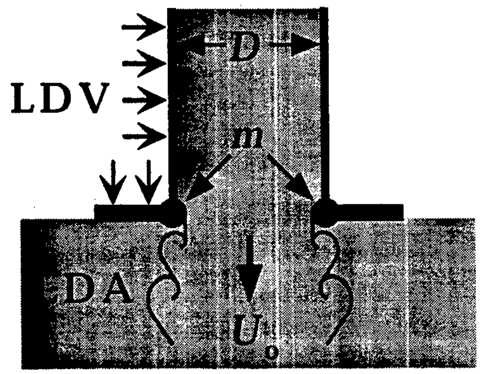

Figure 2: Schematic of pipe-hull coupling experiments.

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